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Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada

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ABSTRACT

Ice-marginal glaciated landscapes demarcate former boundaries of the continental ice sheets. Throughout circumpolar regions, permafrost has preserved relict ground ice and glacigenic sediments, delaying the sequence of postglacial landscape change that transformed temperate environments millennia earlier. Here we show that within 7×10^6 km^2 of glaciated permafrost terrain, extensive landscapes remain poised for major climate-driven change. Across northwestern Canada, 60–100-km-wide concentric swaths of thaw slump–affected terrain delineate the maximum and recessional positions of the Laurentide Ice Sheet. These landscapes comprise ~17% of continuous permafrost terrain in a 1.27×10^6 km^2 study area, indicating widespread preservation of late Pleistocene ground ice. These thaw slump, relict ground ice, and glacigenic terrain associations are also evident at the circumpolar scale. Recent intensification of thaw slumping across northwestern Canada has mobilized primary glacial sediments, triggering a cascade of fluvial, lacustrine, and coastal effects. These geologically significant processes, highlighted by the spatial distribution of thaw slumps and patterns of fluvial sediment mobilization, signal the climate-driven renewal of deglaciation and postglacial permafrost landscape evolution.

INTRODUCTION

Coupled climate-terrestrial models predict widespread degradation of near-surface permafrost over the next century (IPCC, 2013), indicating that thawing of ice-rich terrain (thermokarst) will be the fundamental mechanism of circumpolar landscape change (Kokelj and Jorgenson, 2013). Rising air and permafrost temperatures and increasing frequency of extreme precipitation are accelerating thermokarst in many regions, altering slopes (Kokelj et al., 2015) (Fig. 1), modifying ecosystems (Chin et al., 2016), and liberating carbon from thawing soils (Schuur et al., 2015). A quantitative geomorphic framework for determining the nature and intensity of thermokarst remains a critical gap in predicting the environmental consequences of circumpolar warming.

Earth systems conditioned by glaciation are termed paraglacial landscapes (Church and Ryder, 1972; Ballantyne, 2002). Deglaciation is a period of dynamic geomorphic change characterized by high sediment fluxes that rapidly diminish as supply is exhausted and landscapes adjust to postglacial conditions. We propose that in circumpolar regions, cold climate and permafrost has maintained glacial landscapes including moraine complexes and glaciofluvial, glaciolacustrine, and glaciomarine deposits in a quasi-stable state (Astakhov and Isayeva, 1988; Dyke and Evans, 2003). These vast stores of frozen sediments host thick layers of ground ice, including massive segregated ice and buried glacier ice (Mackay, 1971; Murton et al., 2005; Evans, 2009). Diffusive processes have smoothed the topography across most of these landscapes. In fluvial and coastal settings, erosion augmented by glacio-isostatic adjustments, and climate-driven thermokarst, have increased topographic gradients (Fig. 1). However, cold climate and permafrost have preserved relict ground ice and limited sediment supply, imposing a fundamental constraint on postglacial landscape evolution.

Retrogressive thaw slumping is a dynamic form of thermokarst (Kokelj and Jorgenson, 2013). The coupling of thermal and geomorphic processes can expose ground ice directly to surface energy fluxes, rapidly degrading ice-rich terrain and modifying slope and valley configurations (Fig. 1; Fig. DR1 in the GSA Data Repository[1]). Thaw slumping degrades buried glacial ice in moraine deposits, transforming contemporary proglacial environments (Evans, 2009). This process has also reworked glacial deposits in temperate regions

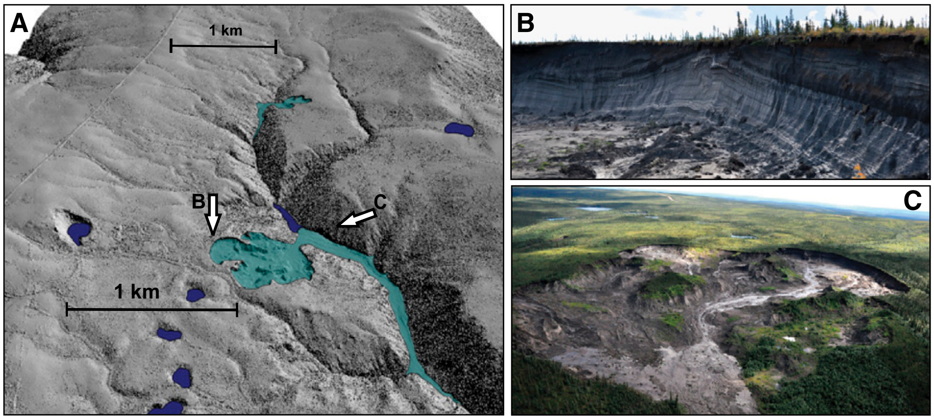

Figure 1. Megaslumps in fluvially incised hummocky moraine, Peel Plateau, northwestern Canada. A: Digital terrain model showing thaw slumps (light blue) in headwater valleys. These slumps, 30 ha and 8 ha, are eroding ~0.5×10^6 m^3 of material per year. The debris tongue in the foreground has a volume of ~3.5×10^6 m^3. B: Banded massive ice in the 30-m-high headwall reveals an ice-cored landscape. C: Saturated materials in the slump scar zone are evacuated by mass flows.

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[1] GSA Data Repository item 2017106, digital data used to create Figure 2A, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

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(Ham and Attig, 1996), and modified glacigenic permafrost landscapes in western Arctic Canada during the early Holocene warm period (Murton, 2001). The recent acceleration of thaw slumping (Segal et al., 2016a) and the development of immense mass-wasting complexes in northwestern Canada demonstrate the efficiency of this climate-sensitive process in mobilizing glacial sediment stores (Fig. 1; Fig. DR1).

To explore the relation between glaciated landscapes and permafrost terrain sensitivity we mapped thaw slumps at regional to continental scales and investigated the nature of fluvial effects. We integrated spatial data on thaw slump distribution and patterns of fluvial sedimentary disturbance with theory on the preservation of relict Pleistocene ground ice (e.g., Murton et al., 2005) and paraglacial landscape change (Ballantyne, 2002) to demonstrate that (1) permafrost has delayed the geomorphic evolution of glaciated terrain, so that these landscapes retain significant potential for climate-driven change; and (2) the patterns and intensity of accelerated thaw slump activity in northwestern Canada and the nature of fluvial effects indicate deglaciation-phase or early postglacial geomorphic dynamics.

METHODS

To investigate the distribution of slump-affected terrain, a 1,274,625 km^2 area of northwestern Canada was mapped using SPOT (Satellite Pour l'Observation de la Terre) 4 and SPOT 5 satellite imagery (A.D. 2005–2010), hosted on the Government of the Northwest Territories (GNWT) Spatial Data Warehouse web viewer (http://www.geomatics.gov.nt.ca/sdw.aspx), to classify 15 × 15 km grid cells according to the density of large active slumps (>1 ha). The grid classes included none (0 slumps), low (<5 active slumps), and medium (6–14 active slumps) to high (≥15 active slumps). The data, consisting of 5665 ranked grid cells, were compiled in ArcGIS 10.0–10.2 (https://www.arcgis.com/; for methods and data, see Segal et al., 2016b).

The association between slump-affected terrain and the late Wisconsinan ice sheet margin (Dyke and Prest, 1987) was assessed using the GLM (generalized linear model) function in "R" (R Core Team, 2013) to perform a logistic regression (family = binomial; link = logit) that modeled the odds (p/q) of disturbance in each grid cell as a function of the Euclidian distance (d) from the ice margin, $p/q = e^{ad+b}$. To examine if broad-scale patterns of thaw slump distribution are supported by fine-scale data sets, we used a digitized slump inventory from the Peel Plateau, northwestern Canada, derived from color satellite imagery (2007–2008; Segal et al., 2016a). Slump-affected terrain in the Peel Plateau was plotted along a 100 km geological transition from unglaciated terrain to moraine to Holocene alluvium.

To investigate the association between thaw slumping and glaciated terrain at the circumpolar scale we mapped the records of relict ground ice and thaw slump occurrences from the published literature. Metadata, ice type, and references are provided in the Data Repository, in addition to the sources of spatial base-layers (Figs. 2A and 2B).

To describe the nature of topographic and sedimentary disturbance resulting from thaw slumping, and to derive order of magnitude estimates of denudation rates, we used a surface model derived from 2011 lidar data from the GNWT. The material volumes displaced by individual thaw slumps were estimated by reconstructing pre-slump topography using contour lines, and then differencing the regridded old topography from the new.

Fine-scale slump mapping in the Peel Plateau and a database of total suspended sediment concentrations (TSS) in streams (n = 198) of the Peel River watershed (80,000 km^2) were used to assess slump-driven fluvial effects. Catchment sizes were estimated using a topographic model derived from the Canadian Digital Elevation Model (20 m resolution) (Government of Canada, 2000). TauDEM (v.5.3) Fill, D8, and Flow Accumulation algorithms (http://hydrology.usu.edu/taudem/; Tarboton, 1997) were applied to trace the drainage network and catchment area upstream of thaw slump and water sampling locations. To investigate the influence of slumping on the fluvial sedimentary regime, TSS concentrations during the summer flow period for streams in the Peel basin were compiled (Kokelj et al., 2013; Chin et al., 2016) and plotted against catchment area. Samples from larger tributaries collected from 2000 to 2005 were provided by the GNWT.

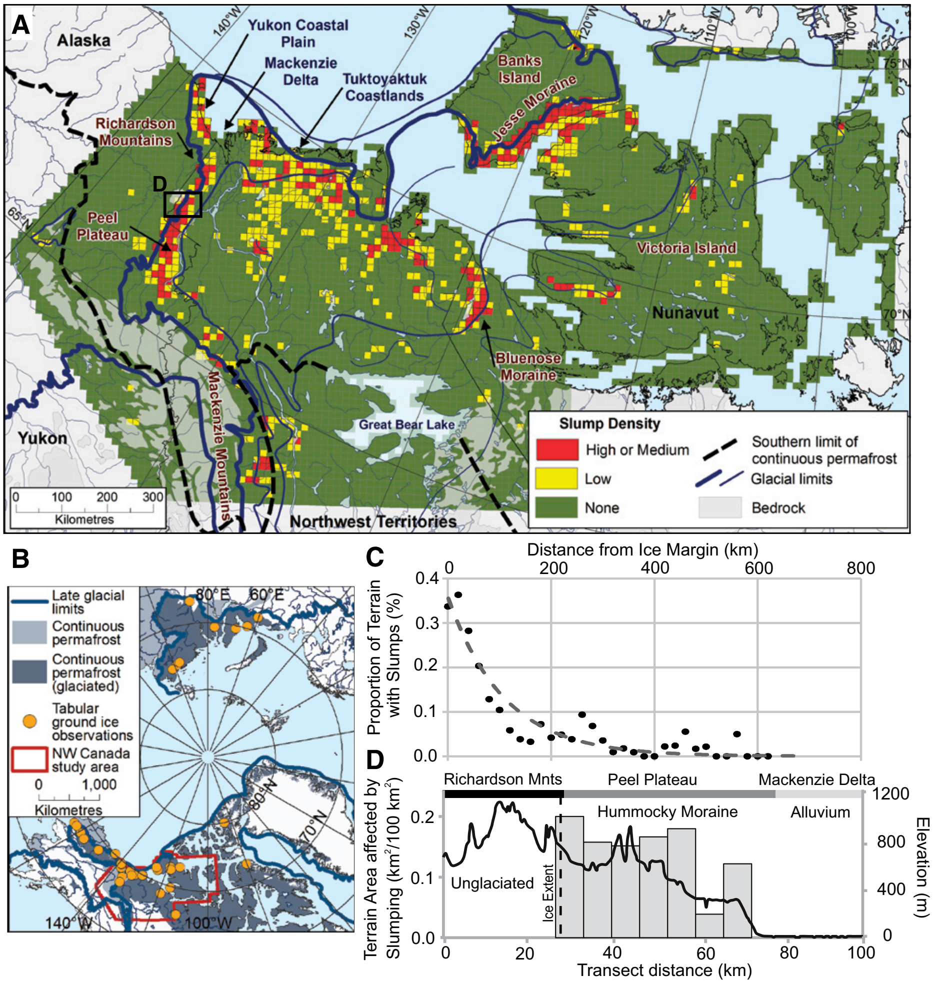

Figure 2. Thaw slump distribution and glaciated terrain. A: Slump-affected terrain in northwestern Canada and positions of the Laurentide Ice Sheet from ca. 18–11 ka. B: Circumpolar map showing published observations of thaw slumps and thick ground ice in glaciated permafrost terrain. C: The proportion of terrain with slumps and distance from the late Wisconsinan ice front (thick blue line in Fig. 2A). A χ^2 test comparing the logistic model to a null model (intercept only) is highly significant (χ^2 = 475.5, P < 0.01). D: Topography and slump-affected area along a west to east corridor (black rectangle in A) through unglaciated terrain, hummocky moraine, and Holocene alluvium.

RESULTS AND DISCUSSION

The mapping of a 1,274,625 km^2 area of northwestern Canada reveals that the distribution of slump-affected terrain is remarkably well constrained by the maximum extent of the Laurentide Ice Sheet (LIS) (Fig. 2A). Because we mapped only larger, active thaw slumps, our estimate of disturbed landscapes exceeding 136,000 km^2 is conservative, but clearly indicates that relict ground ice was extensively preserved along recessional margins of the LIS throughout continuous permafrost of northwestern Canada (Fig. 2A). The compilation of published observations from the circumpolar Arctic (Fig. 2B; Fig. DR1) also shows the close association between thaw slumping and ice-marginal glaciated terrain interpreted to host relict ground ice. These massive ice deposits are typically associated with hummocky moraine, but are also present in glaciofluvial, glaciolacustrine, and isostatically uplifted glaciomarine deposits.

Glacial legacy has an overriding influence on permafrost terrain sensitivity across northwestern Canada. Figure 2A shows that a 2700-km-long swath of slump-affected landscape extends from the eastern slopes of the Cordillera in southern continuous permafrost to the Arctic Islands. This broad strip of slump-affected terrain is bounded by recessional margins of the LIS, and occupies an area >45,000 km^2. The distribution of slump-affected terrain shows a significant exponential decrease with distance from the late Wisconsinan ice front (Fig. 2C). Hundreds of kilometers to the east of the maximum LIS extent, recessional ice sheet positions are occupied by a well-defined but broken string of slump-affected moraine complexes covering an area >30,000 km^2 (Figs. 2A and 2C). Fine-scale mapping from the Peel Plateau confirms the broad-scale associations between slumping and glacigenic deposits (Fig. 2) (Lacelle et al., 2015; Segal et al., 2016a). Figure 2D shows that thaw slumps occur throughout the ice-marginal moraine complex, but are absent from adjacent unglaciated terrain and Holocene alluvium.

Several factors combine to influence the distribution and intensity of thaw slumping in glaciated permafrost landscapes. The eastward decline in thaw slump occurrence across northwestern Canada (Figs. 2A and 2C) coincides with the transition from hummocky moraine and ice-thrust landforms deposited along the debris-rich polythermal western margins of the LIS to a bedrock-dominated shield landscape with a thin cover of till (Dyke and Prest, 1987). The mountainous margins of the Cordilleran ice sheet with thin glacial drift also contain few slumps (Fig. 2A). More than 90% of the slump-affected glaciated terrain is in continuous permafrost (Fig. 2A), consistent with the circumpolar pattern (Fig. 2B). A latitudinal decline in slump-affected terrain (Figs. 2A and 2C) follows a transition to discontinuous permafrost where past thawing has likely degraded much of the near-surface relict ground ice. Discontinuous permafrost characterizes ~30% of the glaciated regions mapped, but hosts only 6% of the slump-affected terrain (Fig. 2A).

Within glaciated continuous permafrost terrain, past climate, ground thermal conditions, topography, and geomorphic settings now combine to influence the broad patterns of terrain sensitivity. The low density of slump occurrence in rolling, thaw-lake–dominated hummocky moraine southeast of the Mackenzie Delta (Fig. 2A) is a function of gentle topographic gradients and thaw truncation or eradication of ground ice by thermokarst during the early Holocene warm period (Burn, 1997; Murton, 2001) or following forest fires. High disturbance densities occur where erosion intensity or relative relief is greater, including coastlines and fluvially incised environments like the Peel Plateau (Figs. 1, 2A, and 2D). The extensive moraine systems on southeastern Banks Island (Lakeman and England, 2012) compose the largest contiguous region of highly disturbed terrain, exceeding 15,000 km^2 in area (Fig. 2A). This suggests that relict ground ice can be well preserved where cold and dry climate and continuous permafrost have constrained past thaw and geomorphic activity. Recent acceleration of slumping has transformed southeastern Banks Island (Segal et al., 2016a) and northwestern Victoria Island into extraordinarily dynamic landscapes (Fig. 2A; Fig. DR1). The distribution of highly disturbed terrain (Fig. 2A) indicates that extensive ice-marginal moraine and isostatically uplifted and fluvially incised glaciolacustrine and glaciomarine deposits in the Arctic Islands retain great potential for climate-driven geomorphic change.

The recent intensification of slumping and thermokarst mobilization of glacial sediment stores demonstrates that permafrost has preserved the potential for climate-driven landscape dynamics, millennia after disappearance of the continental ice sheets (Figs. 2A and 2B). In northwestern Canada, slumping has transformed thousands of headwater catchments into major sediment source areas (Figs. 1, 2A, and 3A), consistent with a deglaciation-phase geomorphic response pattern (Ballantyne, 2002). Major thaw slump features can transfer 10^4 to 10^5 t km^{-2} yr^{-1} of material from slopes to stream valleys (Fig. 1), suggesting that sediment flux from slump-influenced headwater systems likely exceeds yield estimates for larger watersheds (Church et al., 1999) by several orders of magnitude. Large slumps now produce massive debris tongues (Kokelj et al., 2015) that fill trunk valleys (Fig. 1), providing a long-term persistent sediment source to downstream fluvial systems. Evidence of disturbance to the fluvial sediment regime is provided in Figure 3A, which shows that TSS concentrations in slump-affected headwater streams (<100 km^2) during summer base flow are several orders of magnitude greater than in undisturbed, unglaciated, and higher order river systems. The inverse association between TSS and watershed scale for slump-affected streams from northwestern Canada (Figs. 3A and 3B) is in stark contrast to glaciated temperate regions where upland sediment sources have long since been exhausted, and the higher sediment yields of large rivers reflect the contemporary reworking of catchment-derived glacial materials (Church and Slaymaker, 1989).

CONCLUSIONS

In circumpolar regions, cold climate and permafrost have delayed the evolution of glaciated landscapes for millennia (Astakhov and Isayeva, 1988), but episodic periods of climate-driven thermokarst (Chipman et al., 2016) can renew postglacial landscape change and transform headwater catchments into major sediment source areas (Figs. 1 and 3). This is an extension of the general model of postglacial landscape evolution where deglaciation, defined as a brief

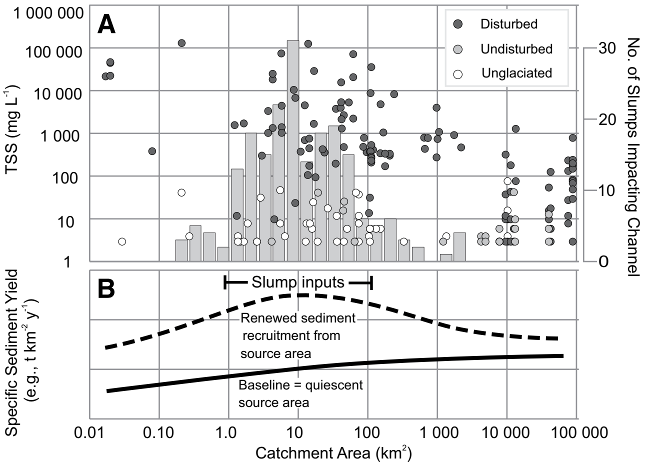

Figure 3. Thaw slumps and disturbance to fluvial systems, Peel River watershed, northwestern Canada. A: The distribution of thaw slumps along fluvial networks in watersheds as large as 10^4 km^2, and total suspended sediment (TSS) concentrations in slump disturbed, undisturbed, and unglaciated streams and rivers throughout the Peel River basin. C: Schematic showing sediment yield-catchment area relations. Solid line approximates baseline conditions in glaciated terrain, northwestern Canada (e.g., Church et al., 1999). The dotted line shows sediment yield against catchment scale for slump-affected glaciated landscapes.

period following glacial retreat, is characterized by rapid sediment mobilization and exhaustion of primary or upland sediment stores (Church and Ryder, 1972; Ballantyne, 2002). These glacigenic materials transit a sequence of fluvial storage reservoirs, and combine to reinforce a sediment delivery signal that cascades for millennia across increasing watershed scales (Church and Slaymaker, 1989). In contrast, the evidence from mapping thaw slumps and analysis of fluvial responses from northwestern Canada indicate that glaciated landscapes underlain by permafrost preserve relict ground ice and have retained significant potential for climate-driven geomorphic transformation millennia after the disappearance of the LIS. This has major implications for predicting the nature and intensity of permafrost landscape change and downstream effects on fluvial, lacustrine, and coastal ecosystems. The regional- to continental-scale imprint of the thaw slump disturbance regime (Fig. 2), its recent intensification, and the fluvial-geomorphic patterns of sediment mobilization (Fig. 3) indicate a rejuvenation of postglacial landscape change. We conclude that extensive glacigenic deposits imprisoned by permafrost are poised for climate-driven geomorphic transformation.

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